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THE RELIABILITY ANALYSIS OF NONELECTRONIC COMPONENTS

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FOREWORD

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PUBLICATION REVIEW

This report has been reviewed and is approved.

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THE RELIABILITY ANALYSIS OF NONELECTRONIC COMPONENTS

INTRODUCTION

The word "reliability" summarizes our knowledge, intuitions and judgement that a system or its constituent parts will do the job for which it is intended. However, to give this concept meaning, and to permit objective measurements and calculations to be made, we must be more specific. What do we mean by "doing the job"? Under what conditions? Is one failure in a series of tests acceptable, or how many?

The problem is even more difficult when we consider the question of meaning. For example, the familiar series rule tells that five components, each of 90% reliability and strung together in series have a combined reliability of 59%. If this is too low and a system reliability of 90% is required, then the five components must each have a reliability of at least 98%. If this level of reliability has been achieved for a given set of conditions any change in conditions will result in a change in the system reliability.

The problem of reliability, in the end, comes down to some standard of satisfactory performance in relation to a set of missions and environments. The estimation, analysis, and demonstration comprise the area of reliability to be discussed in this paper.

This paper will consider the three topics from the point of view of mechanical and electromechanical equipments. Most reliability analysis work done to date has been in the area of electronic items. There is good reason for this. For one thing, very large numbers are applied in a well defined mission under fairly consistent environments. Therefore, the essential conditions noted are quite reasonably specified. Furthermore, it was found that mature electronic equipments had failure patterns at least reasonably well described by the very easily managed exponential distribution. That is to say, it was found that to a reasonably good approximation, the failure rate was constant with time.

Mechanical and electromechanical components have quite different failure responses. Tests and common observations suggest that failures vary with time. Hence, an hypothesis of random failure is not a valid one. Rather, a reliability statement for such components must certainly include time, and because of statistical reasons connected with the precision of measurement, must also contain a random term. Mathematically this might be written: $R(t) = f(t) \times \eta$.

Where: $f(t) = F[A(t), E(t), R_1(t)]$,

and: A = application factor
E = environmental derating factor
R_1 = inherent reliability

The best evidence presently available indicates that the above items may be expressed as a product, i.e., $A \; E \; R_1$ provided $0 \leq AE \leq 1$.

Eta, η, equals an error term which represents both the inherent variability of A, E, and R_1, and the uncertainty arising from measurement errors. The situation is by no means black simply because the exponential expression does not seem applicable.*

While it may be true that because of the small dimensions in which electrical processes occur, there is a very long step between fundamental physical considerations and test phenomena so that reliance must essentially be placed on statistical techniques. On the other hand, nonelectronic components are of relatively huge dimensions. Illustrative of this point is a comparison of an electron (approximately 10^{-13} cm with a mean free path in the order of 10^{-12} cm) with the 10^{-1} or 10^{-2} cm free path of even precision mechanical assemblies. This is the very difference which may permit usage of not only statistical properties, but also specific engineering mechanisms of failure, i.e., at the macroscopic level. This is the rationale which permits f (t) to be written in terms of physical phenomena.

As any card player knows, a good peek at the opponent's hand is worth any amount of probability analysis. In this sense, with an understanding of causal relationships leading to failure events, positive statements can be made which can be used to develop conventional designs on a reliability basis.

CAUSAL ANALYSIS

Causal explanations of failure in terms of mechanisms of failure should play a key role in the reliability analysis of nonelectronic components. This is not suggestive that the random or probabilistic element can be excluded, but rather that the object is to make this term as small as possible in comparison with the effects that are deterministically measured. This is analogous to determining a physical constant, i.e., the constant is measured with standard apparatus and procedure, and the results are stated plus or minus an error term.

This approach is most applicable to components whose failure can be attributed to relatively few mechanisms, and in which the failure phenomena are well determined by such mechanisms. As previously noted, this approach for physical reasons may be more hopefully applied to nonelectronic parts than electronic parts.

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* The exponential expression has been applied with seemingly good success to the reliability prediction of short-lived systems such as missiles. Because of the short use time, it is generally conceded that wearout failures are negligible. Chance failure then emerges as the primary mode of failure and the use of the exponential is justified.

The approach suggested also recognizes that many parts cannot be analyzed on a purely statistical basis because of size, cost, or time constraints on testing. Unless the number of samples is sufficiently large, the prediction of reliability would be based on tests that produce a confidence interval so wide as to offer no guide to practical engineering. Also, the conditions of use and of failure detection are such that the classical assumptions that underlie accepted reliability theory are patently not pertinent.

Since it would be absurd to claim more than any approach can deliver, the only claim made for this approach is that as a scientific method it pays attention to the following:

1. A close study of the life history of environmental stresses, i.e., how the component is used and what failure inducing stresses it encounters through its life.

2. Relates a modest number of mechanisms of failure to these environments.

3. Expresses failure rates as a function of time corresponding to each stage of the equipment life history.

4. Considers the probability of occurrence of a terminal or killing stress, and the integral of the cumulative damage over each stage of its life history.

This approach leads to an estimate of life expectancy, by factors. If the probability of a killing stress is small, the design may be regarded as properly adapted for the mission environment. If the life expectancy, expressed as a probability, is inadequate to the mission, corrective measures such as protection or periodic replacement can be resorted to. Product improvement can be directed against the factor that is the major contributor to the failure rate equation. This approach is, therefore, not only descriptive but also prescriptive.

Conventional probability procedures suggest the concept of the weakest link and improving the reliability situation by strengthening the weakest link. However, as with the Deacon's one horse shay, an object with all links of equal strength is not necessarily the best answer. The Deacon used the strongest and best materials and the shay ran perfectly for a very long time until:

> ".....it went to pieces all at once - all at once, and nothing first - just as bubbles do when they burst".

The Deacon had used past experience of the reliability of each element to obtain uniform longevity of all parts without any intervening maintenance. The complexity of modern equipment, however, necessitates many maintenance and use cycles during the operational life.

The life history of components and equipments is a continuous process in which different stress/failure mechanisms occur. A typical life history would generally be as follows:

1. Material selection
2. Fabrication
3. Inspection
4. Packaging/storage
5. Transportation/installation
6. Operation

A key point in deterministic reliability is to keep the number of phases to a minimum consistent with the incidences and probabilities of the failure causing mechanisms. As an example, if the use, maintenance or inspection operations involve the physical handling of cables and connections, then this becomes a factor in the life history since there is a failure hazard in the flexing of standard connections.

Even in theoretically repetitive situations, the stress placed on a component will vary from one cycle to the next. The characteristics of a given component will vary from one unit to another by virtue of manufacturing tolerances, materials variability, quality control, and specification tolerances. The purpose of strength-stress analysis is to determine, in common terms, the strength-stress distributions, and the degree of overlap. This overlap defines the failure probability area.

ENVIRONMENTAL CONSIDERATIONS

In the analytical approach, it is necessary to determine which of the stresses have a cumulative damage effect and which have no effect provided the critical stress level is not exceeded. The cumulative stresses must be included since the damage is a function of time.

The effect of combined stresses is an area in which very little data exists and in which much more research is needed. Many combinations of stress produce synergistic effects while others are mutually inhibiting.

ELECTROMECHANICAL FAILURE MECHANISMS

In reviewing the failures of electromechanical components it has been found that relays fail primarily because of contact failure. Relay contacts may be said to act as a resistance with two discrete values, one corresponding to an open position, and the other to a closed position. A contact failure may be said to have occurred if the closed resistance is too high or the open resistance is too low.

Among the chief causes of contact failure are: (1) contamination or constriction of the contact surfaces which result in contact arcing, melting, and mechanical wear; (2) mechanical shifting or oscillation in the make/break operation.

Contact contamination may result from dust in the manufacturing plant, material of the relay itself, or as the result of the fabrication processes.

Constriction is caused by the deterioration of the contact surface due to contamination, or by a change in the geometry of the contact surface.

Melting of a pair of contacts may be caused by contamination and the constriction of current flow. A relay that carries a considerable current load generates a large amount of heat. If the temperature of the metal rises above the melting point and it is allowed to cool quickly, the contacts may weld.

Arcing is another phenomena which produces relay failure. As the contacts separate, the current conduction area is reduced and the current density increases. As a consequence, the temperature of the material increases as does the potential drop across the contacts. As physical contact is lost, conduction continues thru ionized metal vapor which forms an arc.

After a large number of operations, relay contacts begin to wear and become unstable. The possibility of wear prohibits the use of soft materials and prevents optimization of such design parameters as electrical and thermal conductivity. Wear problems are particularly significant in the design of subminiature and microminiature relays where the gap must be small and the contact dimensions caused by wear are relatively large.

SWITCH FAILURE EXPERIENCE

Experience, in the form of empirical data, has shown that the life of a switch varies directly with the current load. In one test, a limit switch was run at 10 milliamps, 115 volts AC, for more than 5×10^7 operations. When the test was terminated, the interior of the switch was clean. A similar switch, run at 5 amps, became so gummed up that it jammed at 4×10^6 operations. A precision switch was operated for 32×10^6 cycles at 1 amp before it jammed. A similar switch operated at 5 amps failed at approximately 3×10^6 cycles.

Figure 1 shows the radical increase in life with decrease in load. For example, assuming 10% maximum allowable failures, the 60 amp test shows that 10% of the switches failed at 2000 cycles. However, decreasing the load to 30 amps raised the 10% point to 8000 cycles. With a further reduction to 10 amps, the 10% point was not reached until 40,000 cycles.

The failure distributions in Figure 1 show other interesting phenomena. The failures are plotted on Weibull distribution paper, and show good fit with a straight line. This infers that, for this particular switch, the failures are well described by the Weibull distribution. More important, the data tends to indicate that the failure patterns are identical for electromechanical and mechanical modes of operation; that is, identical with and without electrical contact load. This is somewhat of an enigma for which no explanation is readily available. It would seem more logical and acceptable if the failure distribution had changed with a change in mode of operation.

The above results are substantiated by another study on the operating life expectancy of two other types of switches as a function of rated load. As shown in Figure 2, a precision limit switch with a derating of the operating load, was found to have a large increase in life expectancy. It is also shown that even a heavy duty limit switch has a similar response.

MECHANICAL FAILURE MECHANISMS

The following examples of failure mechanisms are presented in order to provide an insight into the varied processes which underlie and produce such mechanisms. No attempt has been made to make this a complete coverage of the topic.

1. Friction and Wear - Surfaces which come into contact with each other under dynamic conditions experience plastic flow, fracture, and thermal processes at the contact points. These lead to deleterious effects to mating surfaces. Oxidation and corrosion of surfaces, and wear debris also contribute to the wearing process.

Adhesion and interlocking of minute surface irregularities are the subjects of a number of theoretical investigations. These wear processes occur on the sliding surfaces of all types of materials.

Although friction is a result of the shearing of the contact junction, the friction level does not necessarily correspond to the wear rate. For example, a large contact area will produce high friction; if adhesion forces between the junctions are low, shearing will take place at the junction interface, with little or no removal or transfer of material and hence little wear.

Wear of steel surfaces is influenced by its tendency to work harden and oxidize. Surface work hardening influences the flow and fracture properties of the contacting surface asperities, while oxidation effects adhesion forces. Work hardened and oxidized wear particles complicate the wear process by acting as loose abrasives. Ruptured oxide film will alter the mode of wear and sometimes contribute to heavy surface damage.

The brittleness and relatively low thermal shock resistance of ceramics will lead to micro-fragmentation with frictional and adhering junctions.

Rubber has low tensile strength, deforms considerably without plastic flow, and forms small surface tears when stretched. This reduction of internal material stress to tangential surface stresses produces a type of wear unique to rubber.

2. Fatigue - The fatigue process is a primary factor which acts to reduce the life expectancy of mechanical and electromechanical parts. Because of the inherent physical qualities of material, fatigue damage is produced by the successions of load imposed on the material during the operational life of the part.

The current philosophy, which has only recently come into use, is to consider the statistical character of the fatigue life of the part, and the scatter associated with loading and part responses. This has necessitated the consideration of the statistical load spectrum, which represents the operational conditions to which the material is subjected. However, a simple load spectrum of a particular material does not, alone, adequately describe the complex operating conditions of an actual assembly over its lifetime.

Significantly different approaches are necessary for the analysis of material fatigue and of the fatigue of a part or assembly. Metal fatigue is a well-defined problem of physics, while structural fatigue must be considered a mechanical reliability engineering problem of a specific design configuration operating in a defined environment. It has been estimated that 90% of the fatigue failures of structures and machine parts are not a function of the fatigue characteristics of the materials, but are the result of faulty design details and production control.

The normal distribution has been applied in the past to describe fatigue failures. However, since a large number of failures can be traced to design deficiencies rather than straight forward material fatigue, they may be better treated in the same manner as wear-out, i.e., by a Weibull distribution.

The Weibull distribution represents the next stage in flexibility over the one parameter exponential and the two parameter normal. It has three parameters: (1) a "shape" parameter which determines what it looks like; (2) a "location" parameter which determines where the shape is located on the time axis; and (3) a "scale" parameter which provides the magnitude of the shape. The Weibull can be fitted to a variety of failure distributions. For example: (1) when the shaping parameter is less than one, a distribution with decreasing failures is described; (2) for a shaping parameter equal to one, the Weibull reduces to the constant failure rate exponential; and (3) for a shaping parameter of three or larger, the function approaches a normal distribution.

RELIABILITY PREDICTION TECHNIQUES

The techniques which follow are in accord with the assertions made in the preceding portions of this paper. That these techniques do not individually incorporate or consider all of the factors, is indicative of the lack of maturity in the state-of-the-art of reliability as it applies to nonelectronic parts or systems of parts.

1. The Freudenthal Approach to Reliability Analysis of Complex Mechanical Structures - Dr. Freudenthal of Columbia University has recently put forth a procedure applicable to the reliability analysis of large structures and complex mechanical systems whose mode of failure is a function of ultimate load and fatigue life, and which can never be tested in sufficient numbers to provide an acceptable statistical foundation.

Since the procedure is quite lengthy and complex in the extreme, in the interest of brevity the procedure is presented in the form of an abstract.

Probabilistic models are necessary in the design of structures because of the statistical nature of, and scatter involved in, the loading, the material, and the response of the structure. The load spectrum of a structure is not constant in amplitude nor is it a single load application, but a combination of high and low loads in a complex spectrum. In general, a structure will be weakened by repeated small loads. From time to time, there are high loads which may cause the weakened structure to fail, or if not, will contribute to the weakening process. A load spectrum, showing the probability density of a given load could be derived for any structure in a particular use. The fatigue life of a structure depends considerably on its stress concentrations and redundancies. Laboratory tests for constant amplitude fatigue on artificial specimens are not useful for the prediction of the fatigue life of structures. A parameter is derived that is correlated to the probability of structural failure by fatigue as opposed to ultimate load failure. Models of failure are then derived for failure by ultimate load and for failure by fatigue, as well as model which states that the probability of fatigue failure of a structure may be considered to be the probability of ultimate load failure of the weakened structure. These models are statistical in nature and expressions for the reliability are derived and analyzed. The models are considered to be about the simplest that fit reality. They are useful largely for comparing the reliabilities of alternate methods or structures.

2. Analysis by Variance - This technique was first proposed by Robert Lusser in July 1951 as a substitute for safety factors in

assuring missile reliability. This approach has since been refined and is in use in industry by numerous companies, one of which is the Columbus Division of North American Aviation. In the simplest terms it is suggested that any device has a distribution of strength values and in operation will be subjected to a distribution of stress values. These distributions may be determined by testing a statistically valid number to failure. A reasonable approximation of the two scatter bands may be found in the normal distribution. Figure 4 is a representation of strength and stress scatter bands. Figure 5 represents the normal distribution and the two parameters, the mean $(\bar{x})$ and the standard deviation (σ). The first step in this technique requires a determination of the distribution of the stress condition by testing or from design requirements so the average stress, $\bar{x}$, and the standard deviation, σ, can be derived as shown in Figure 6. A reliability boundary is then established, as shown in Figure 6, by adding a given number of standard stress deviations to the average stress value. The number of standard deviations to be added is dependent on the confidence which can be placed on the estimate of the stress environment with the number lying in the range of 4 to 8. The device is then tested to determine the distribution of strength with the reliability of the device then being a function of the number of standard strength deviations separating the average strength and the reliability boundary as shown in Figure 7. The primary deficiency of this approach lies in the fact that no numerical value can be easily derived to express the probability of success. It should also be pointed out that the two curves will intersect since the tails go to infinity and hence there will always remain a probability of failure. The approach also suffers from several argumentation assumptions which are: (1) there is no reduction of strength thru damage accumulation caused by cyclic stress and thus there is no change in reliability in succeeding life intervals; and (2) no allowance is made for the occurrence of chance failures.

3. <u>A Simplified Deterministic Approach</u> - The approach which will now be discussed will provide a quantified estimate of reliability over a useful life period and hopefully is applicable to most non-electronic parts. This approach may be classified as an engineering approach since it uses as its basis the strengths of engineering materials. The graphic representation of strength under dynamic stress conditions takes the form of a plot of stress versus cycles of operation which is commonly called an S-N curve (Figure 8). The parameter of interest in these curves is the endurance limit. It is a characteristic of many materials that as the stress is reduced, the life increases and that at a particular point on the S-N curve a relatively small decrease in stress results in an increase in life to apparent infinity. Thus, it is generally accepted that parts whose operational stress fall between 0 and S_e will have an infinite life. It also follows that parts whose operational stresses are greater than the E value will have a finite life.

Now certain assumptions will be made: (1) Failure of parts stressed below S_e will occur in a random catastrophic fashion which can be well described by the exponential function; (2) Failures resulting from operation at stress levels greater than the E value will be normally distributed; (3) The material characteristics indicated by the S-N curves provide a good approximation of the strengths of the fabricated parts; and (4) That there is no failure relationship between the constituent parts of the device.

With these assumptions in mind, the reliability analysis of a nonelectronic device may be conducted as follows: The operational stress of each constituent part will be examined in relationship to the applicable S-N curve. Those parts found to be operating within endurance limits will be assigned constant failure rates. The total effect of these parts can then be computed using the exponential distribution and the product rule.

$$R_e = e^{-\lambda_1 t} \cdot e^{-\lambda_2 t} \cdot e^{-\lambda_3 t} \ldots = e^{-(\lambda_1 + \lambda_2 + \lambda_3 + \ldots)t}$$

For those parts found to be operating at stresses above the endurance limit, the life can be found from the appropriate S-N curve as a function of the operating stress. Since the normal distribution has been assumed, this value will be then taken as the mean and the standard deviation obtained either through tests or experience. The reliability can then be found by the equations shown in Figure 9. Since we have assumed that there is no failure relationship, it is permissible to invoke the product rule such that the reliability of the device for any "use Life" is $R(\text{total}) = R_e \cdot R_n$.

As stated, the accuracy of this model is entirely dependent on the degree of validity of the basic assumptions and also the precision to which the operational stresses are determined. None the less this approach can provide a useful quantified estimate of the reliability of nonelectronic devices employed in ground electronic systems and may be directly introduced into the current approach to the analysis of electronic systems.

CONTRACTUAL SUPPORT

The American Power Jet work for RADC under Contract AF30(602)-2652 deals with the investigation of reliability prediction for mechanical and electromechanical components applicable to ground electronic systems. The principle areas of investigation cover the following topics and the discussion is organized under these headings:

1. Evaluation and analysis of available failure data.

2. Investigation and development of applicable mathematical model.

3. Investigation of effect of trade-offs on failure rates, including stress level, duty cycles, maintenance, cost, etc.

4. Investigation of applicable failure mechanisms.

5. Investigation of manufacturing process variability effect on failure rates.

6. Effect of load sequencing on useful life.

7. Preparation of specification requirements.

The requirement was to establish a general structure of theory and analysis technique applicable to all components and parts. However, in consideration of the funding, the effort was to be concentrated on a specific list of mechanical and electromechanical parts which occur frequently in ground-based electronic systems, which are failure significant items, and for which data might be expected to exist. These comprise:

1. Actuators
2. Bearings
3. Cables
4. Clutches
5. Connectors
6. Counters
7. Couplings
8. Fasteners
9. Gears
10. Motors
11. Potentiometers
12. Relays
13. Rheostats
14. Solenoids
15. Switches
16. Synchros

The comments should be read in the context of these items.

1. Evaluation and Analysis of Available Failure Data

A wide variety of data sources were investigated. In general, it was found that present failure data collections leave much to be desired with regard to consistency of data base, absence of failure (as distinct from qualification test) information, and almost total lack of time variant information. The Air Force failure and reporting system (787-1 and 66-1) in their present form do not contain certain essential elements of information, e.g., time of exposure, definitive information as to the mode of failure. Information collected from manufacturers, and trade associations is frequently informative with regard to causal factors, but is invariably quantitatively thin.

Original data collection and investigation was therefore undertaken in the 413L and 465L systems. Each failure event for a period of two years from the 413L system was investigated. A total sample of about 2300 failure events involving the above-listed components were obtained from this system. Eleven months of data on the 465L system revealed 200 failures. The 465L tests were under a controlled environment prototype operation under laboratory conditions.

Relay failures were the most frequent, accounting for close to 50 per cent of all failures. Motors, switches, and bearings followed in order.

Failure information is available in the categories of "corrective" and "preventive". Corrective maintenance is performed after a failure occurs; preventive maintenance represents the removal of the component prior to the time which it actually fails. It will be seen therefore that there is a certain subjective element in the totality of removals (the judgement of the maintenance man). This is particularly important in as much as all the items covered are "condition" (items removed when they are deemed unsatisfactory) in contrast to "time" items (which are removed upon the expiration of a given time interval).

Figure 10 gives a typical set of distributions of failure events by category of occurrence. During the two years of data investigated, there was a strong shift from corrective to preventive maintenance removal in several categories, reflecting maintenance management changes in thinking.

The failure patterns for individual components listed are being studied over the time interval. It is worth noting that there exists no reasonably accurate parts count for many major Air Force ground electronic systems. This implies that failure rates of individual components can scarcely be put on a comparable basis without additional work. This is being done for the 413L system.

The failure distributions, when normalized to a four-day or weekly period of time, were found to be quite well approximated by essentially Poisson distributions. Thus, the exponents in the distribution may tentatively be stated as follows:

Component	4-day base	Weekly base
Motors	1.6 x 7=11.2	3.0 x 4=12.0
Bearings	.9 x 7= 6.3	1.8 x 4= 7.2
Switches	1.2 x 7= 8.4	2.2 x 4= 8.8
Relays	3.0 x 7=21.0	5.2 x 4=20.8

To anticipate a portion of the discussion under a succeeding section, we may note that statistical techniques were established in which the commensurateness of the Poisson exponents for two alternative periods of time were used to establish and test that the underlying distribution is exponential or Weibull. This amounts to stating:

$$\frac{\lambda_1 \Delta t_2}{\lambda_2 \Delta t_1} = K$$

where K is the Weibull parameter.

The foregoing empirical data demonstrates this point for the components investigated. The quality of fit is noteworthy. It should be recalled at this point that component failures which have an underlying exponential or Weibull failure distribution produce a Poisson distribution of number of failures during equal time intervals, when the part or components failed are being replaced. The technique established also determines the Weibull parameter by evaluating the ratio of the lambdas.

Work along these lines is in process for both corrective and preventive phases. It will be seen that these data lead to useful insights not only regarding the failure distribution but also with regard to the appropriate maintenance and replacement policy to attain maximum system effectiveness.

A further line of investigation which has considerable promise is the derating studies which industrial users perform on components such as relays and switches. These, however, provide qualitative rather than quantitative insights, i.e., the data thus far examined appears to relate more closely to the product of individual manufacturers than to design characteristics or industry state-of-the-art. But enough data has been located to offer promise of substantial improvement in this situation with further work.

In summary, the evaluation and analysis of available failure data emphasizes the urgent need for consistent, standardized and commensurate data reporting in a format containing the essential elements of information of time, failure mode, operating conditions, environmental and application factors, etc. It further demonstrates that specific investigations along the lines of those described above do in fact disclose patterns having high predictive value. Finally, it demonstrates the importance of detailed work as a prerequisite to any generalization of results.

2. Investigation and Development of Applicable Mathematical Models

The underlying approach to the mathematical model requires that the result be consistent with the techniques established in the RADC Reliability Notebook. This essentially implies a technique in which the electromechanical reliability formulation is commensurate with the electronic terms in the total reliability expression. In view of the promising results of the Weibull and exponential plots discussed above, this is obviously the case (it will be recalled that in Generalized Poisson processes, the exponents may properly be combined).

Previous detailed statements of the model structure emphasize the value of considering quite separately the "inherent reliability" which is essentially a consequence of the engineering state-of-the-art, and "application factor" which corresponds to the mission use stresses, and the "environmental factor" corresponding to the environmental stresses seen by the equipment, and a final term for the probability of "catastrophic events". These will not be repeated at this point.

Theoretical work in progress shows promise of producing sound descriptions of processes in which wear-out and catastrophic failure are superposed. The subject would not be left without noting the intimate interrelation among (a) mathematical theory and models, (b) the available data to verify or test these models, and (c) the predictive purposes envisioned.

3. Investigation of Trade-Offs

In the previous paragraphs the effect of corrective versus preventive maintenance on failure rates has been noted. Studies of derating present the effect of stress level and duty cycle on service life.

Numerical evidence has not been established which will allow a positive assertion regarding the effect of relative part cost on failure rates. While it seems reasonable that cost may be directly related to failure rates, the proof requires further effort.

The investigation of the effect of load sequencing (discussed below) provides further inputs to the analysis of trade-offs since the load sequence implies alternations in the load cycle, duty cycle, stress level, etc.

4. Investigation of Applicable Failure Mechanisms

The attack on this problem has been through the preparation of a structure of information which is termed a "Handbook of Failure Mechanisms". The approach to this handbook is to first compile a list of the different types of each component under study (e.g., bearings - ball and roller). Within each type of component, a matrix of component parts versus the corresponding type of component is given. For example, given a certain type of bearing it is possible to determine what are the parts which make up its construction. This is followed by a second matrix which relates the mode of failure for each part, setting forth the major mechanism of failure operative on the part (established from empirical and engineering analysis), and the secondary modes which also appear.

Therefore, given a component, the designer may consider the parts which are most susceptible to the environmental and applications stresses (by consulting the mechanisms of failure) and taking the appropriate protective or design counter-measures.

The data collected on the 413L system was further utilized to establish a verification matrix which is presented separately in the handbook. Two matrices (dealing with preventive and corrective actions separately) list the cause of failure as reported by the maintenance personnel. These are used to establish relative weighting factors so that the component-part-mechanism of failure relationship can be used to guide preventive versus corrective maintenance directives for any given ground electronic system.

This work is presently in process but shows distinct promise and clearly merits extension and expansion.

In summary, the approach to the mechanisms of failure has been to link physically observed data to engineering insights and test results. To the best of our knowledge, neither this approach nor its empirical verification have been reported elsewhere.

The analysis of mechanisms of failure which is here pursued at a component-part level is further extended and exploited at a materials level in the discussion of "load sequence" below.

5. Investigation of Manufacturing Process Variability on Failure Rate

This phase of work is still actively in process and it is still too early to report on the result. However, large scale statistical data from the field which reflects differences in manufacturing have not been located to date. This is reasonable in as much as military equipments must meet acceptance specifications which in most cases leave little latitude as to the means of fabricating a given item for a given function. Quite conceivably, procurements now being initiated under the various "breakout" programs will provide information on equipments made by different manufacturers according to different processes. But this experience is for the future, since the number of components thus far procured have been relatively few. There is more promise in work at the level of material or tests.

6. Effect of Load Sequencing on Useful Life

The approach to load sequencing on useful life is approached on a material level (consistent with its place in the hierarchy of part-component discussed in the failure mechanisms section). Here the major mechanisms of failure which are involved in load sequencing are taken as (a) fatigue, (b) creep or stress rupture, (c) impact, (d) corrosion, (e) wear, (f) thermal failure. Each of these categories is dissected into a load sequence parameter and an effect. Thus fatigue is caused by cyclic or fluctuating stress and is manifested by fracture, cracks, spalls, or crazing. This approach may be envisioned as a species of transfer functions, i.e., the cyclic or fluctuating stress is the forcing function and the response is the fracture, etc. Similar inputs and outputs are established for the other mechanisms (see Table I).

Then the loads (application or environmental) which are seen by the electromechanical or mechanical component are analyzed. Thus mechanical loads consist of tension, compression, shear, torsion, and bending. Electrical, chemical, thermal, and natural environmental loads are similarly structured. This concept was evaluated in a pilot study of relays and has been found sufficiently promising to warrant further exploitation and application to the other components in so far as time and funds permit.

The work on load sequencing completes the logic of materials-parts-components closely integrated with the data and mathematical model concept.

7. Preparation of Specification Requirements

It is evident that the utilization of the information set forth in the preceding section can make a direct contribution to specifications for individual components. Work under this phase of the work program is directed to the "template" which should be used to verify that a reliability specification is complete and correct. Thus, work under this phase, still in progress, will establish the requirements which must be fulfilled by a responsive reliability specification.

In summary, within the very limited resources available to the work program, the field has been thoroughly surveyed, a series of promising avenues have been opened for investigation, substantive results have been made available in specific areas, and lines for further responsive effort established.

CONCLUSIONS

In summary, it has been shown that the approach to the reliability prediction of nonelectronic parts can best be served by basing the technique on the mechanisms of failure. This can be brought about by transforming deterministic models relating to these mechanisms into probabilistic time domain models.

The three techniques presented are in consonance with the philosophy developed. While a large degree of immaturity can be noted in these techniques, no apologies are necessary since they reflect the state-of-the-art.

The greatest needs, if the art is to be advanced, are as follows:

1. The establishment of a failure data collection and analysis system specifically for nonelectronic parts. This would overcome the present lack of empirical data.

2. Institute further investigations into the damage resulting from the progression of critical failure inducing mechanisms as a function of stress versus time.

3. Institute studies in the area of the synergistic and/or inhibiting effects resulting from combinations of stress.

4. The development of efficient means for the generation of empirical failure data and verification of predictions.

5. The development of unifying laws to explain the interrelationships among the entire spectrum of failure mechanisms.

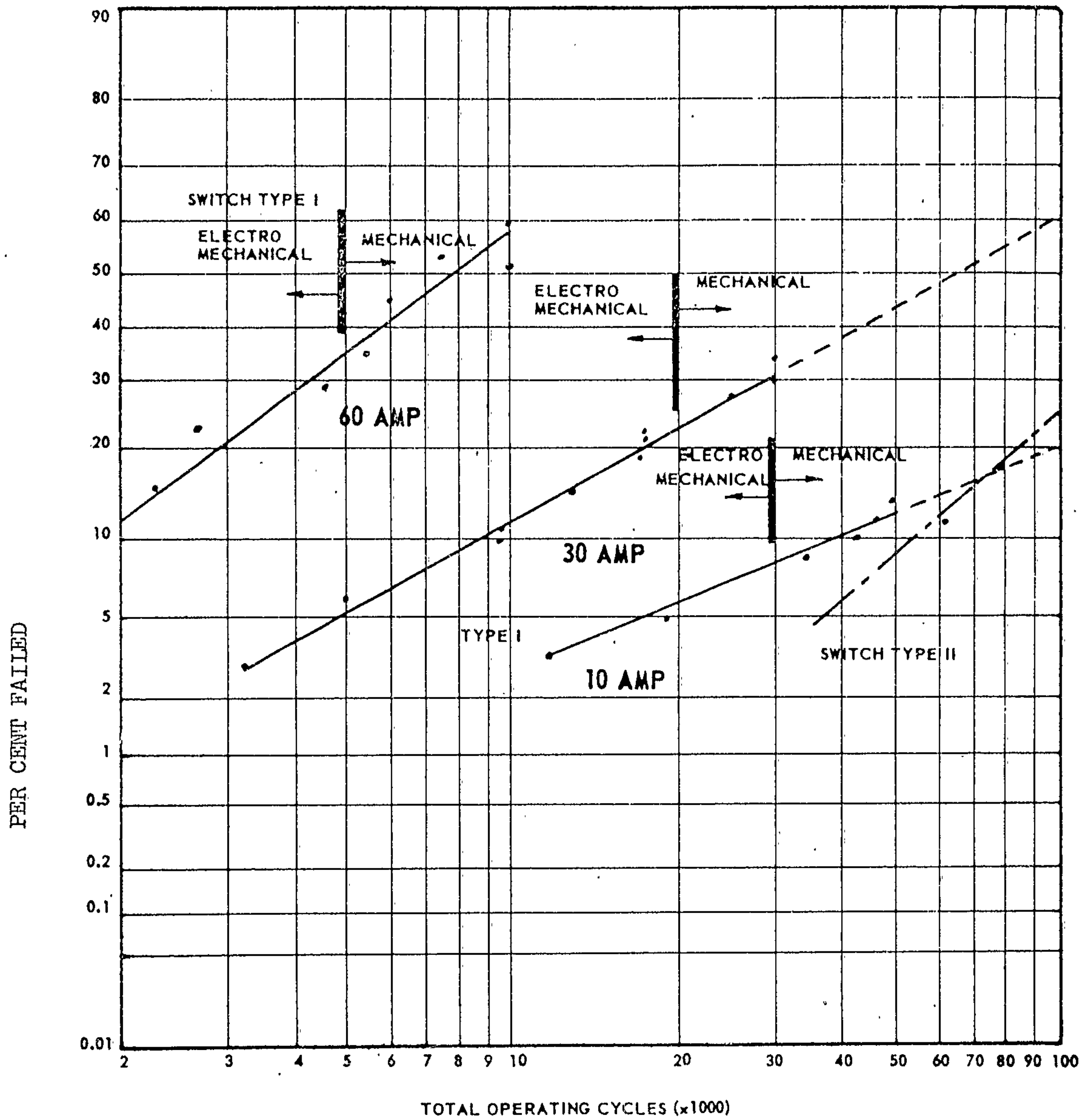


Figure 1 Electromechanical Switch Reliability

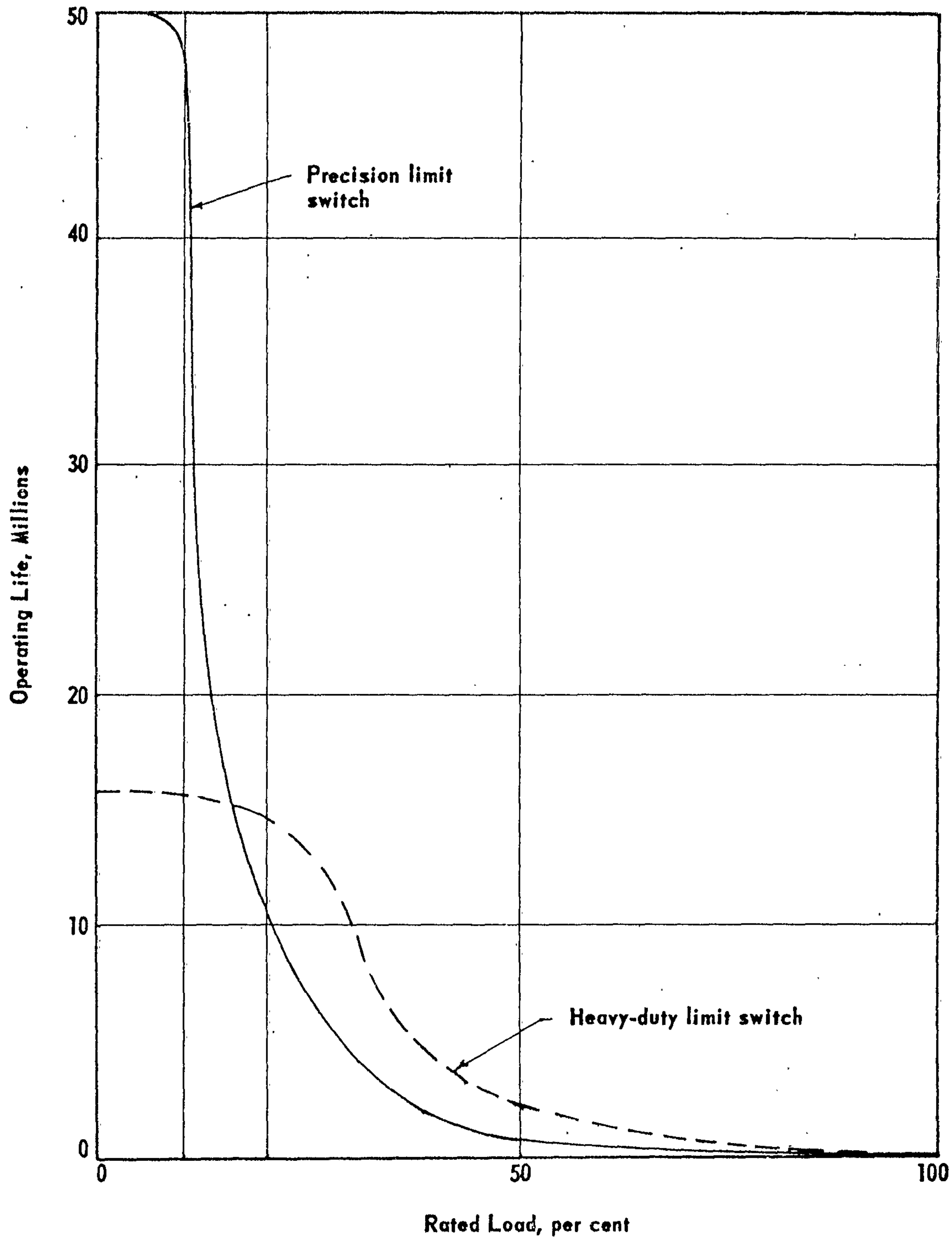
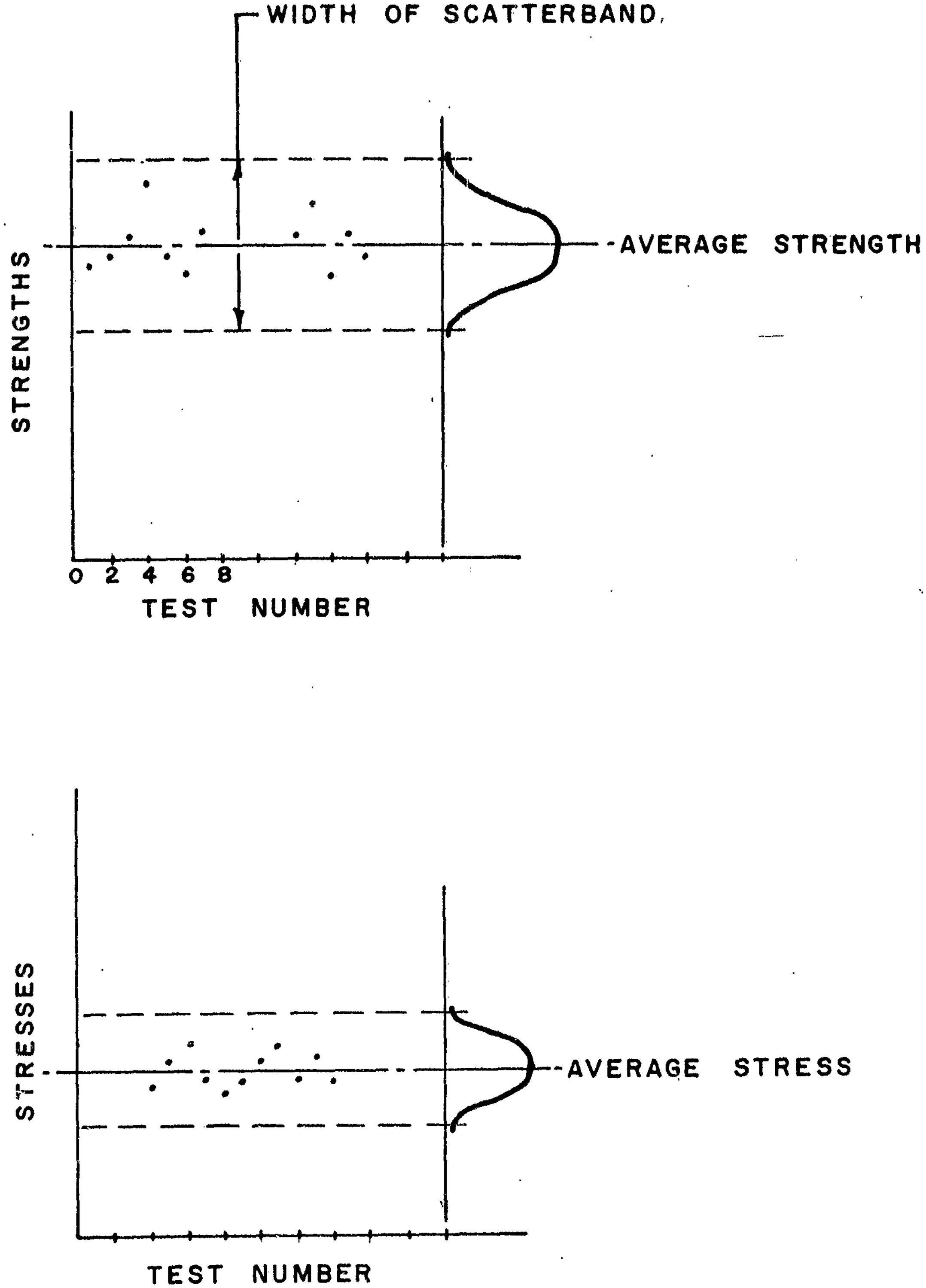
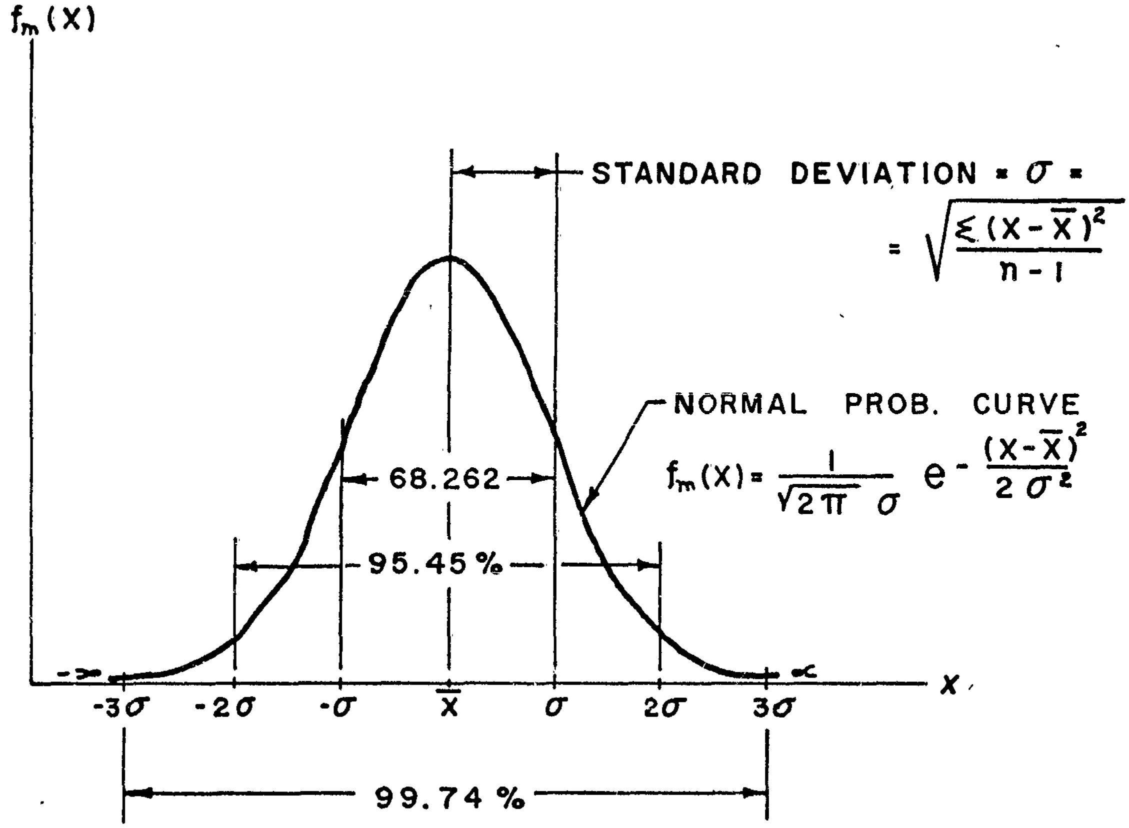


Figure 2 Rating of Contacts on Limit Switches With Respect to Load-Life



STRENGTH-STRESS SCATTER BANDS

FIG. NO. 4



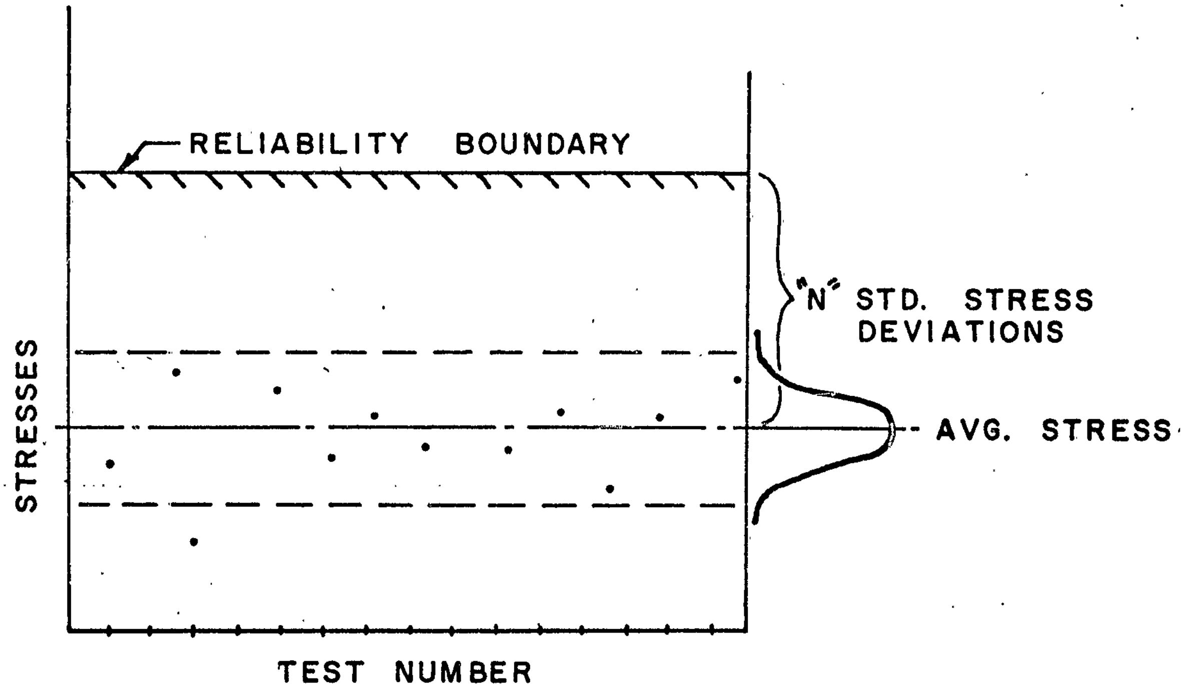
ARITHMETIC MEAN $= \bar{X} = \frac{\Sigma X}{n}$

WHERE: ΣX = SUM OF OBSERVATIONS CONSTITUTING THE SAMPLE.

n = NUMBER OF OBSERVATIONS CONSTITUTING THE SAMPLE.

NORMAL DISTRIBUTIONS

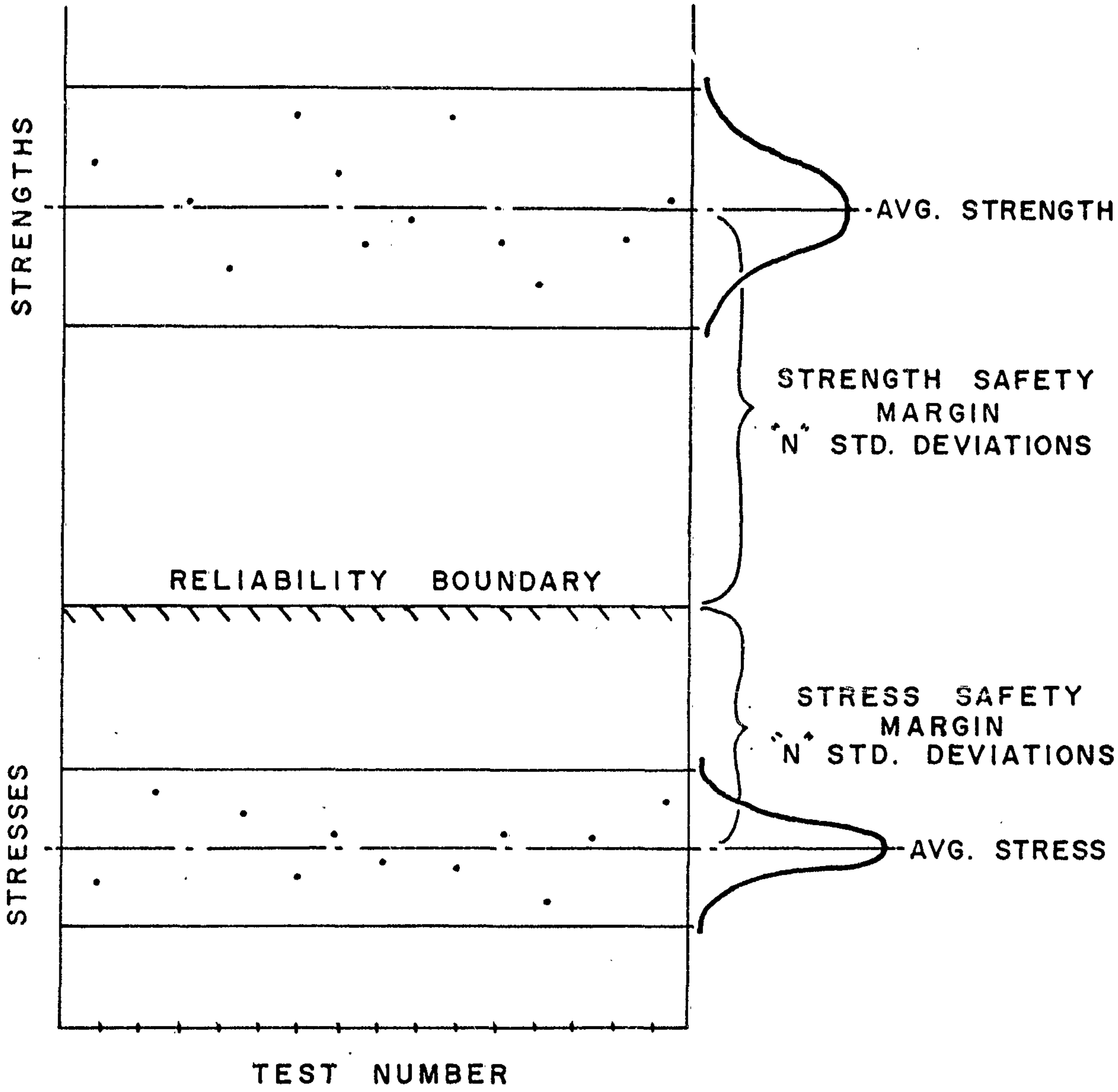
FIG. NO. 5



$$\text{STD. DEVIATIONS} = \sigma = \sqrt{\frac{\Sigma (X - \bar{X})^2}{n - 1}}$$

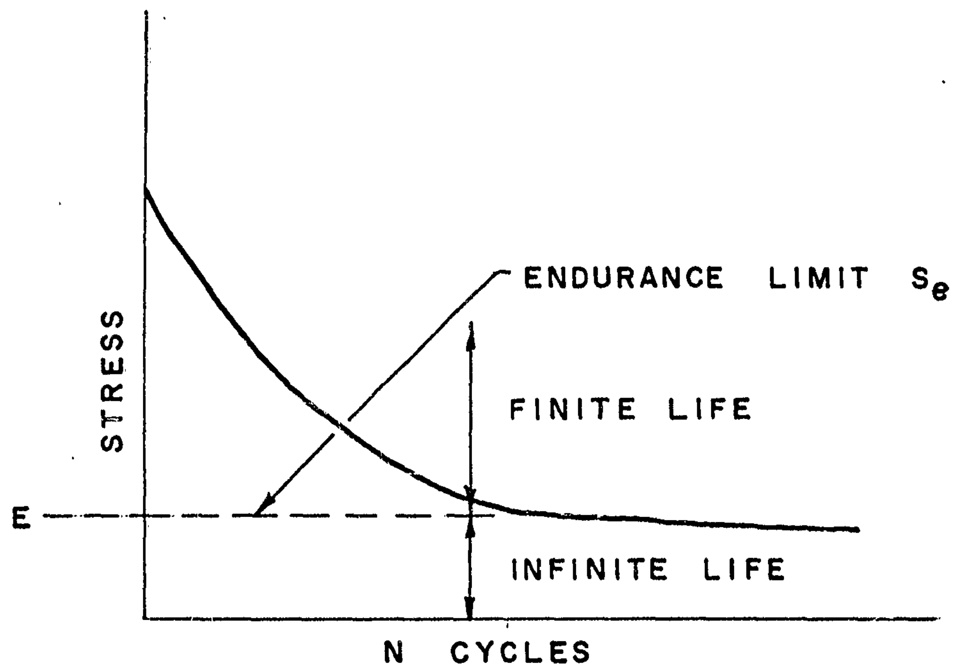
RELIABILITY BOUNDARY

FIG. NO. 6



SAFETY MARGIN

FIG. NO. 7



TYPICAL S-N CURVE

FIG. NO. 8

$$P_f = \int_{-\infty}^{z} f(t)\,dt$$

WHERE : f (t) IS THE NORMAL PROBABILITY DENSITY FUNCTION.

$$Z = \frac{t - \bar{t}}{\sigma}$$

AND $R = P_S = 1 - P_f = 1 - \int_{-\infty}^{z} f(t)\,dt$

RELIABILITY NORMAL EQUATION

FIG. NO. 9

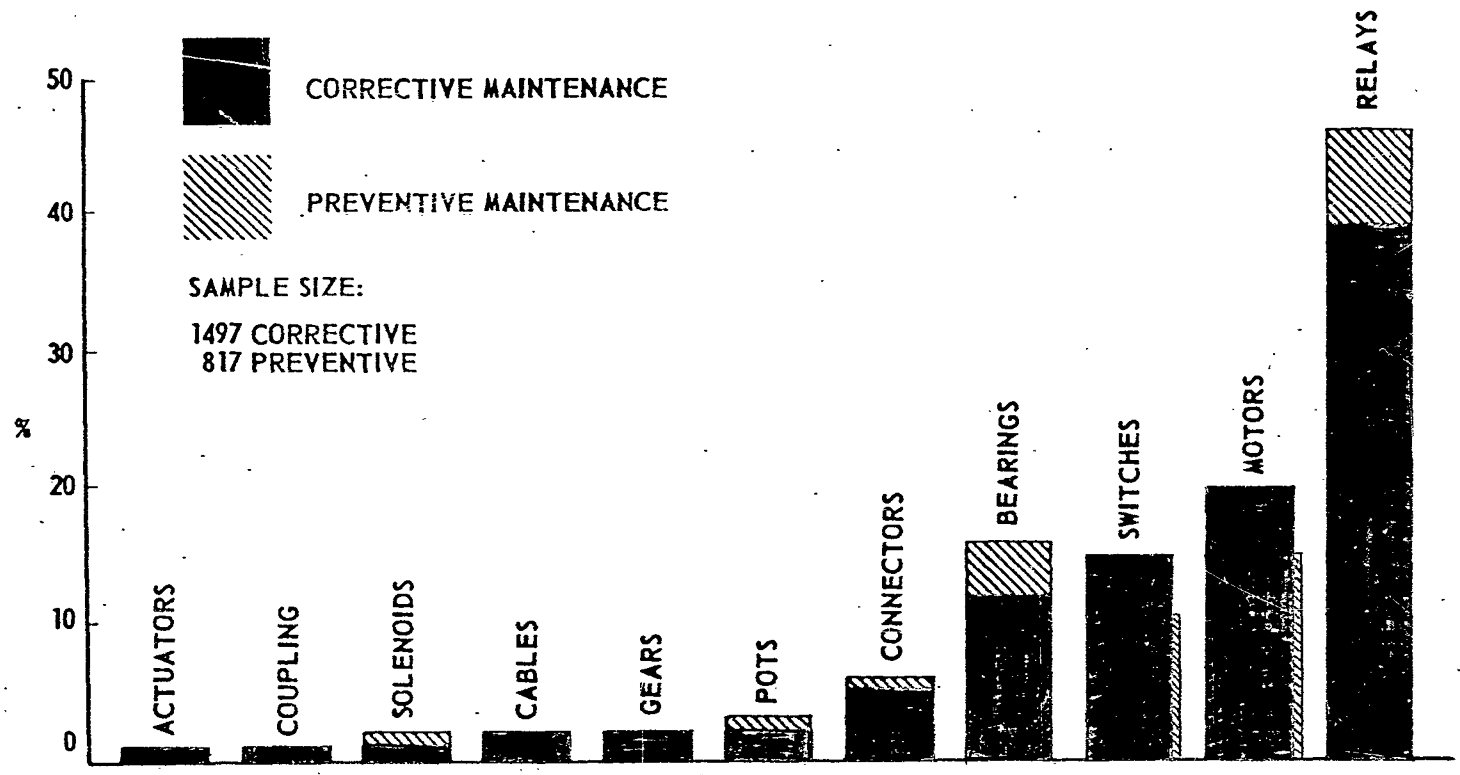


Figure 10

COMPONENT FAILURES AS A PERCENT OF TOTAL FAILURES
(CORRECTIVE AND PREVENTIVE)

TABLE I
FAILURE MECHANISMS DEFINITION

FAILURE MECHANISMS	LOAD	TIME	DEFINITIONS
Fatigue	Repeated or Fluctuating Mechanical	Extended	Phenomena leading to failure under repeated or flucutating stress less then the tensile strength.
Creep or Stress Rupture	Constant or Static Mechanical	Brief or extended	Phenomena leading to failure under constant load and temperature in a period of time.
Impact	Constant, moving mechanical	Instantaneous	Phenomena leading to failure as a result of the sudden application of a moving load.
Corrosion	Chemical or Chemical and Mechanical	Brief or extended	Deterioration of a metal by chemical or electrochemical reaction.
Wear	Various Mechanical	Brief or extended	Removal of material from a solid surface as a result of mechanical action.
Thermal	Thermal	Brief or extended	Deterioration of material by melting, vaporization, decomposition and welding as a result of high temperatures.

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